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Environmental and economic analysis of switchgrass production for water quality improvement in northeast Kansas

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Abstract

The primary objectives of this research were to determine SWAT model predicted reductions in four water quality indicators (sediment yield, surface runoff, nitrate nitrogen (NO_3–N) in surface runoff, and edge-of-field erosion) associated with producing switchgrass (*Panicum virgatum*) on cropland in the Delaware basin in northeast Kansas, and evaluate switchgrass break-even prices. The magnitude of potential switchgrass water quality payments based on using switchgrass as an alternative energy source was also estimated. SWAT model simulations showed that between 527,000 and 1.27 million metric tons (Mg) of switchgrass could be produced annually across the basin depending upon nitrogen (N) fertilizer application levels (0–224 kg N ha^{-1}). The predicted reductions in sediment yield, surface runoff, NO_3–N in surface runoff, and edge-of-field erosion as a result of switchgrass plantings were 99, 55, 34, and 98%, respectively. The average annual cost per hectare for switchgrass ranged from about $190 with no N applied to around $345 at 224 kg N ha^{-1} applied. Edge-of-field break-even price per Mg ranged from around $41 with no N applied to slightly less than $25 at 224 kg N ha^{-1} applied. A majority of the switchgrass produced had an edge-of-field break-even price of $30 Mg^{-1} or less. Savings of at least 50% in each of the four water quality indicators could be attained for an edge-of-field break-even price of $22–$27.49 Mg^{-1}.

Keywords: SWAT model; Switchgrass production; Economic analysis; Commodity crops; Water quality; Sediment yield; Surface runoff; Soil erosion

1. Introduction

The impact on the environment of greenhouse gases such as carbon dioxide (CO_2), in conjunction with recent increases in petroleum fuel costs, have prompted a genuine concern regarding our continued reliance on petroleum-based fuels and their effect on air quality and energy security. Carbon dioxide emissions from energy use are projected to increase on average by 1.5 percent per year from 2002 to 2025, to 8142 million metric tons (United States Department of Energy, 2004). Since 1990, primary energy consumption in the United States has increased by 14% (28% in the last 25 years) and is forecast to increase another 40% by 2025 (United States Department of Energy, 2004). Clearly, the environmental, economic, and energy consequences associated with imported petroleum call for additional research.

Renewable energy has distinct environmental advantages associated with its production and use. Most renewable energy technologies such as solar and wind produce no direct emissions. Biomass energy crops such as agricultural crop residues can, under judicious management, be harvested for alternative energy purposes (e.g. bioethanol production) and still provide adequate protection from soil erosion and needed soil tilth. Other biomass energy resources, such as herbaceous and woody energy crops, offer a wide range of environmental benefits and can have a positive environmental impact. Some environmental benefits associated with herbaceous and woody energy crops include:

1. Reduced water and wind produced soil erosion;
2. Reduced surface and subsurface fertilizer and pesticide migration, improving surface and groundwater quality;
3. Reduced emissions of global warming gases and carbon sequestration in root systems more extensive than annual crops; and
4. Improved regional air quality by reducing SO_2 and NO_2 emissions.

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Non-point source (NPS) pollution of streams, lakes, and reservoirs from sediment, fertilizers, and pesticides is a significant threat to water supplies, waterways, and wildlife habitats in many parts of the country. The United States Environmental Protection Agency (EPA) 2000 National Water Quality Inventory (United States Environmental Protection Agency, 2000) found that sedimentation remains one of the most widespread pollutants affecting assessed rivers and streams, impairing 84,503 river and stream miles (12% of the assessed river and stream miles and 31% of the impaired river and stream miles). Sedimentation alters aquatic habitat, suffocates fish eggs and bottom-dwelling organisms, and can interfere with drinking water treatment processes and recreational use of a river. In addition to rivers and streams, sedimentation pollutes nearly 1.6 million lake acres (9% of the assessed lake acres and 21% of the impaired lake acres). Often, several pollutants and processes impair a single lake. For example, an activity such as removal of shoreline vegetation may accelerate erosion of sediment and nutrients into a lake. Other federal agencies have reported similar findings. The United States Department of Agriculture-Agricultural Research Service (USDA-ARS) considers sediment the primary contaminant in rivers, lakes, and reservoirs. The United States Geological Survey (USGS) has estimated nearly one-third of all water bodies in the continental United States are at least moderately, and in some cases, severely polluted due to non-point source pollution. Most NPS pollution problems are attributable to production agriculture. Intense agricultural land use is leading to rapid sedimentation in many Kansas reservoirs, including Perry reservoir in the Delaware basin in northeast Kansas. Sources of non-point source pollution include sediment from runoff on agricultural lands, nutrients such as nitrogen (N) and phosphorus (P), and pesticides. The state of Kansas performed an assessment (Kansas Department of Health and Environment, 1999) that prioritized 72 watersheds/reservoirs into three separate categories for meeting state water quality standards regarding sediment and nutrient loadings. Category 1 watersheds were those in need of immediate restoration and protection, Category 2 watersheds were those in need of protection only, and Category 3 watersheds were those having pristine and sensitive conditions associated with them. Over 77% of the state's watersheds were classified as Category 1; the watershed considered in this study, the Delaware, was assigned to this category (Kansas Department of Health and Environment, 1999).

One promising strategy to help significantly reduce sediment, surface runoff, and nutrient loading into Kansas streams, tributaries, and reservoirs is to plant perennial warm season grasses such as switchgrass (*Panicum virgatum*) in selected locations within watersheds. In a recent analysis, Kansas investigators found that the use of switchgrass resulted in reduced soil erosion from rainfall as well as general reductions in nutrient loss in runoff and subsurface flow versus all conventional commodity crops across the state (King et al., 1998). Soil erosion from rainfall was reduced an average of 99% and runoff was significantly reduced by bioenergy crop production.

Switchgrass is regarded as a highly promising energy crop with an average energy yield of approximately 260.8 GJ ha^{-1} at a production level of approximately 14+ Mg ha^{-1} y^{-1} in northeast Kansas. Potential markets in Kansas include co-firing with coal in a utility boiler and pelleting for space and water heating. Both strategies have energy-profit ratios (energy output/total energy input) between six and 12. The above analysis concluded, however, that switchgrass could not compete with fossil fuels at existing prices (King et al., 1998).

One strategy for reducing the cost of switchgrass is to determine the extent of surface water quality benefits associated with its production and use through a reduction in soil erosion (sediment transport) and nutrient runoff compared to conventional commodity crop production, and place a monetary value on these benefits. The actual monetary value could be in the form of a payment to either the landowner or utility based on the amount of soil (sediment) saved or a percent reduction in N and P transported from the field in sediment or surface runoff. By planting switchgrass in selected locations throughout a watershed, it may be possible to add decades to the physical and economic life of such reservoirs. Therefore, the major objective of this research was to estimate the environmental benefits and economic feasibility of producing switchgrass for water quality improvement in the Delaware basin of northeast Kansas versus conventional cropping rotations and quantify the environmental (water quality) benefits associated with switchgrass production. Specific objectives were to:

1. Use the soil and water assessment tool (SWAT) model to evaluate the impact of switchgrass production on sediment yield, surface runoff, NO_3-N in surface runoff, and edge-of-field erosion in the Delaware basin. Switchgrass production was evaluated on agricultural croplands that typically produce corn, soybeans, grain sorghum, and wheat commodity crops;
2. Use the SWAT model to simulate switchgrass and commodity crop yields and then evaluate the break-even cost associated with producing switchgrass versus conventional cropping rotations in the Delaware basin; and
3. Estimate, based on information gained in the first two objectives, the magnitude of a switchgrass water quality payment (based on switchgrass production in place of traditional commodity crops) required to decrease sediment loadings 10, 25, and 40% into Perry reservoir in the Delaware basin.

2. Methods

2.1. SWAT model overview

The soil and water assessment tool (SWAT) model (Arnold et al., 1998; Neitsch et al., 2002) was developed to assist water resource managers in predicting and assessing the impact of management on water, sediment and agricultural chemical yields in large ungaged watersheds or river basins. The model is intended for long-term yield predictions and is not capable of detailed, single-event flood routing. SWAT is a physically-based model and has eight major components—hydrology, weather, sediment transport, soil temperature, crop growth, nutrients, pesticides, and agricultural management.

For modeling purposes, SWAT partitions watersheds or basins into a number of sub-watersheds or sub-basins based on climate, hydrologic response units (HRUs), ponds/reservoirs, groundwater, and the main channel or reach draining the sub-basin. HRUs are homogeneous land areas within the sub-basin comprised of unique land cover, soil, and management combinations. The daily water budget in each HRU is computed based on daily precipitation, runoff, evapotranspiration (ET), percolation, and return flow from the subsurface and groundwater flow. Runoff volume in each HRU is computed using the Soil Conservation Service or SCS (1972) runoff curve number approach (USDA Soil Conservation Service, 1972). A recent addition to SWAT is a Green-Ampt (1911) infiltration module to compute runoff volume (Green and Ampt, 1911). Peak runoff rate is computed using a modification to the Rational method (Williams, 1995) or using the SCS TR-55 method (USDA Soil Conservation Service, 1986). Lateral subsurface flow is computed using a kinematic storage model (Sloan et al., 1983) and groundwater flow is calculated using empirical relations. Channel runoff routing is based on the variable storage coefficient method (Williams, 1969); channel flow is computed using Manning's equation with adjustments for transmission losses, evaporation, diversions, and return flow (Arnold et al., 1995). Reservoir flow routing is based on a water balance approach and user-provided measured or targeted outflow. Sediment yield is computed using the Modified Universal Soil Loss Equation (MUSLE) factors (Williams and Berndt, 1977) expressed in terms of runoff volume, peak flow, and Universal Soil Loss Equation (USLE) factors (Wischmeier and Smith, 1978). Channel sediment routing is based on the stream power concept (Bagnold, 1977), modified for bed degradation and sediment transport (Williams, 1980). Bed degradation is adjusted with USLE soil erodibility and cover factors, and deposition is based on particle fall velocity. Reservoir sediment routing is based on a simple continuity equation on volumes and concentrations of inflow, outflow, and reservoir storage. Amounts of NO_3–N contained in runoff, lateral flow, and percolation are estimated as products of the water volumes and the average concentration. A single plant growth model that can differentiate between annual and perennial plants is used to simulate all types of land covers (Williams, 1995). Annual plants grow from the planting date to the harvest date or until the accumulated heat units equal the potential heat units for the plant. Perennial plants maintain their root systems throughout the year, becoming dormant after frost. They resume growth when the average daily air temperature exceeds the minimum, or base, temperature required. The plant growth model is used to assess removal of water and nutrients from the root zone, transpiration, and biomass/yield production.

SWAT tracks the movement and transformation of several forms of nitrogen and phosphorus in the watershed. Nutrients may be introduced to the main channel and transported downstream through surface runoff and lateral subsurface flow. Plant use of nitrogen is estimated using the supply and demand approach described in the section on plant growth. In addition to plant use, nitrate and organic N may be removed from the soil via mass flow of water. Amounts of NO_3–N contained in runoff, lateral flow and percolation are estimated as products of the volume of water and the average concentration of nitrate in the layer. Organic N transport with sediment is calculated with a loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1972) for application to individual runoff events. The loading function estimates the daily organic N runoff loss based on the concentration of organic N in the top soil layer, the sediment yield, and the enrichment ratio. The enrichment ratio is the concentration of organic N in the sediment divided by that in the soil. Soluble phosphorous (P) loss in surface runoff is based on partitioning P between the solution and sediment phases (Knisel, 1980), and is predicted using the labile P concentration in the top soil layer, runoff volume, and a partitioning factor. Sediment transport of P is simulated using a loading function similar to organic N transport. Pesticide transport is simulated using methodology from the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model pesticide component (Leonard et al., 1987) which is based on plant leaf area index, application efficiency, wash-off fraction, organic carbon adsorption coefficient, and exponential decay according to pesticide half-life. In-stream nutrient transformations are simulated with a modified form of the QUAL2E model (Ramanarayanan et al., 1996) with components algae (as chlorophyll-*a*) dissolved oxygen, carbonaceous oxygen demand, organic N, ammonium-N, nitrite-N, nitrate-N, organic P, and soluble P. Water temperature is estimated from air temperature using a regression relation (Stefan and Preud'homme (1993) developed from numerous river observations. Major in-stream pesticide processes simulated by SWAT include settling, burial, re-suspension, volatilization, diffusion and transformation (Chapra, 1997).

2.2. Delaware basin description and creation of SWAT input files

The Delaware river basin covers approximately 300,000 ha in Nemaha, Brown, Jackson, Atchison, and Jefferson Counties of northeast Kansas of which approximately 119,400 ha are cultivated cropland. Grassland and woodland cover approximately 57% of the basin. KSU cooperative extension service field agents as well as USDA district conservationists were asked in telephone interviews about the cropping rotations, approximate percentage of acreage each occupies in the Delaware river basin, and percent that each rotation was subjected to conventional, conservation, or no-till in the Delaware basin.

The four major cropping rotations within the basin are: (1) corn–soybean; (2) corn–soybean–wheat; (3) grain sorghum–soybean; and (4) grain sorghum–soybean–wheat. One extremely minor rotation ($<1\%$ of acreage), corn–soybean–wheat–grain sorghum, was not included in this analysis. The corn–soybean and grain sorghum–soybean rotations are the major cropping rotations within the basin covering 63 and 21% of the total cropland area, respectively. Conservation/reduced tillage is used in approximately 43% of the basin while conventional and no-till operations comprise areas of 29 and 28%, respectively.

The first stage in setting up the Delaware basin SWAT simulation was to define the relative arrangement of the parts or elements, i.e. the configuration of the watershed. A 30 m digital elevation model (DEM) of the Delaware basin was imported into the Geographic Resources Analysis Support System (GRASS, v. 4.1) geographic information system (GIS). The GRASS command r.watershed was then used to delineate (i.e. divide for purposes of flow routing) the Delaware basin into smaller sub-basins. Fig. 1 shows the 45 sub-basin areas identified, including location of the main channel and tributary channels. Individual HRU delineation was performed by overlaying GIS coverages of Delaware basin land use, major cropping systems (if land use was agricultural), and the Natural Resources Conservation Service (NRCS) STATSGO soil database for Delaware basin soils. Non-agricultural land use areas were then filtered out and HRU physical characteristics such as area, slope, dominant soil type, and dominant cropping system were calculated. A total of 552 distinct HRUs (within the 45 sub-basins) were identified.

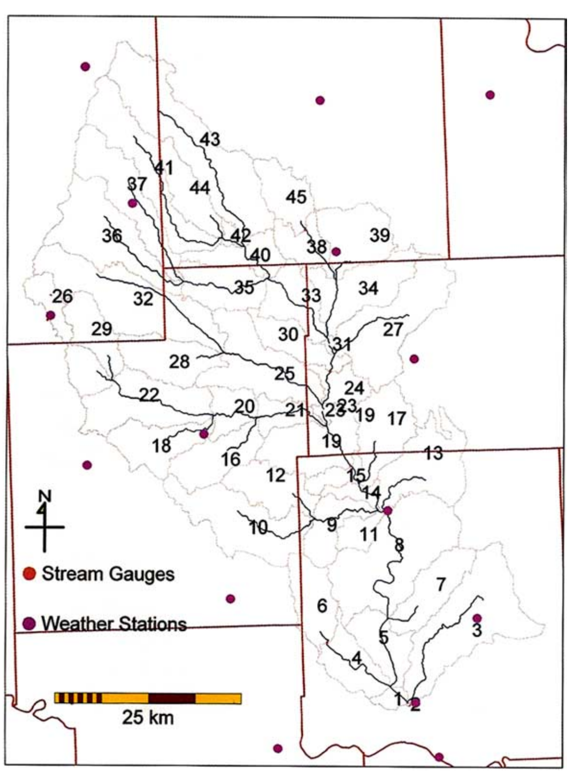

Fig. 1. GRASS GIS delineation of Delaware sub-basins and channels.

SWAT climate files for precipitation and temperature were developed using historical climate data (1966–1989) collected from instrumented weather stations within the basin. Data from nine precipitation stations and five temperature stations were used. Values for solar radiation, wind speed, and relative humidity were generated by the model. Detailed historical climate data were available from 1964–1989, however, the data from the first 2 years contained many missing values and were judged to be unreliable. Therefore, the 24-year period from 1966–1989 was used for all SWAT simulations and subsequent environmental and economic analyses.

General HRU attributes, especially topographic information, were chiefly derived using information acquired from the GRASS GIS watershed delineation exercise. Other HRU attributes, such as parameters affecting erosion (e.g. USLE contouring factors) were determined based on information obtained from KSU cooperative extension service personnel. Soil input files were developed using the NRCS STATSGO soil database for the Delaware basin. Land management input files (e.g. tillage and nutrient applications) were developed using field management operations obtained from KSU cooperative extension personnel and from KSU farm management guides.

2.3. Economic budgets

The economic analysis performed in this study was concerned with determining the break-even price for switchgrass at which farmers/landowners would be indifferent to producing switchgrass in place of each of the four cropping rotations. Farmers will want have at least the same potential income from switchgrass production (as an alternative energy source), versus what they currently are producing and what they feel they will be profitable in future years. In either case, (conventional commodity crop or switchgrass production) as is true with agricultural production in general, an element of risk is always involved.

To accomplish this, the net return to land and management per hectare associated with each commodity crop production rotation was estimated for all 552 HRUs and these returns were used to set the edge-of-field switchgrass break-even price ($\$\ ha^{-1}$ and $\$\ Mg^{-1}$). These prices, in conjunction with a previous analysis of pelleting and using the switchgrass as an alternative energy source for space heating (King, 1999), were used to determine a potential state water quality payment required to entice farmers/landowners to implement switchgrass production for water quality improvement.

Cost-of-production budgets ($\$\ ha^{-1}$) were obtained from KSU cooperative extension personnel and assembled for each of the four commodity crops for conventional, conservation, and no-till field operations where applicable. Typical cost expense estimates were obtained from crop rotation specific farm management guides for Northeast Kansas. The total cost, TC, of production for each particular crop considered consists of production cost (PC), an inflection (extra harvest) cost (INFC) where applicable, and an interest cost (INTC). Production costs vary by crop and the type of tillage scenario employed (e.g. conventional, conservation, or no-till).

Production costs include seed, herbicide, insecticides, fertilizers and lime, drying, and tillage expenses. The inflection cost represents an extra cost associated with harvesting operations and is the product of the difference between the actual yield at harvest and a crop specific base yield and multiplier. Base yield values (bushels ha^{-1}) and associated multipliers at which the inflection parameter is applicable are 202.5 and 0.102, 83.9 and 0.126, 150.7 and 0.110, and 56.8 and 0.124 for corn, soybeans, grain sorghum, and wheat, respectively.

The interest cost is simply the sum of the production and inflection costs multiplied by 0.05. This is a common method for estimating interest in commodity crop budgets. Total cost is the sum of PC, INFC, and INTC. Eq. (1) presents the relationship between the three parameters for the total cost associated with commodity crop production:

$$\mathrm{TC} = \mathrm{PC} + \mathrm{INTC} + \mathrm{INFC} = [\mathrm{PC} + 0.05 \times (\mathrm{PC} + \mathrm{INFC}) + (\mathrm{YLD}_{ci} - \mathrm{BaseYLD}_{c}) \times \mathrm{Inflc}_{parm}] \quad (1)$$

where TC is the total cost associated with production ($\$\ ha^{-1}$), PC are production costs ($\$\ ha^{-1}$), INTC is the interest cost ($\$\ ha^{-1}$), INFC is the inflection cost (function of harvest yield) ($\$\ ha^{-1}$), YLD_{ci} is the harvest yield of a specific crop (bushels ha^{-1}), $\mathrm{BaseYLD}_c$ is the base yield below which an inflection cost does not appear (bushels ha^{-1}), and Inflc_{parm} is the inflection cost parameter as a function of yield ($\$\ bushel^{-1}$).

Estimates of switchgrass cost of production were obtained from farm management guides associated with haying operations in northeast Kansas. Switchgrass production entails establishment costs and annual costs for harvesting. Establishment costs are concerned with preparing the field for switchgrass planting and involve tilling the field to prepare the seedbed. These tilling operations occur only once in the 8–10 y cycle of production and usually involve, depending upon the previous cropping rotation, disking and cultivating.

Annual operations involve fertilizer application, harvesting operations that involve swathing and baling the crop. This analysis only considered harvesting once per year. Harvesting costs were presented as a function of the tonnage harvested and were assigned a value of $10.58 Mg^{-1} harvested. Establishment cost associated with switchgrass production were amortized to obtain an annualized cost (i.e. seed, planting, and tillage cost were amortized to obtain an annualized cost).

Net return to land and management represents a residual return the farmer/landowner can expect to receive for the commodity crops that comprise the rotation(s) produced on the particular soil type comprising the HRU farmed. It is a function of the cropping rotation selected, the field management practice (i.e. tillage scenario) used, and grain/oilseed price. The net return per hectare (NR, $\$\ ha^{-1}$) for each of the four commodity crops is given by Eq. (2):

$$\mathrm{NR} = (\mathrm{CY} \times \mathrm{HP}) - \mathrm{TC} \quad (2)$$

where CY is crop yield (bushels ha^{-1}) and HP is the harvest price ($\$\ bushel^{-1}$). Long-term projected harvest grain and oilseed crop prices ($\$\ bushel^{-1}$) for northeast Kansas were obtained from an analysis performed by the KSU Department of Agricultural Economics (Kastens et al., 2000). These prices were $2.20 for corn, $5.37 for soybeans, $2.11 for grain sorghum, and $3.17 for winter wheat. These price projections were used in the subsequent calculations to determine the net return per hectare for each rotation produced on each HRU.

Net returns to land and management were calculated for each commodity crop on each of the 552 HRUs for each year of the analysis, averaged over the 24-year simulation period, and sorted by each of the four cropping rotations for future analysis. Net returns were computed using simulated yields derived from the SWAT model, long-term prices, and total costs associated with producing each commodity.

For farmers/landowners to be indifferent to producing switchgrass versus commodity crops, they would need to realize an edge-of-field net return equal to that of any one of the four rotations. This required 'target' net return helps to set the edge-of-field break-even price for switchgrass which is directly related to the final delivered cost of energy-whether it be for switchgrass pelleting for space and water heating, use as a co-fire fuel for electricity generation, or as a base feedstock for bioethanol production. The break-even price is a function of three factors: the cropping rotation net return per hectare, the total cost of producing switchgrass (a function of N application level), and expected yield. The edge-of-field break-even price of switchgrass (BEPSWG, $\$\ Mg^{-1}$) is given in Eq. (3):

$$\mathrm{BEPSWG} = (\mathrm{NR} + \mathrm{TPCSWG})/(\mathrm{YLDSWG}) \quad (3)$$

where NR is the net return ($\$\ ha^{-1}$) from the production of commodity crops, TPCSWG is the total production cost for switchgrass ($\$\ ha^{-1}$), and YLDSWG is switchgrass yield ($Mg\ ha^{-1}$).

3. Results and discussion

3.1. Environmental analysis

The environmental analysis portion of this project was concerned largely with determining the reduction in the four water quality indicators (sediment yield, surface runoff, NO_3–N in surface runoff, and edge-of-field erosion) entering Perry reservoir as a function of producing switchgrass on all parcels of conventional cropland acreage within the Delaware basin. The analysis was based on the 1966–89 24-year modeling period using historical climate data as described above. Annual values were simulated for the four environmental indicators over the 24-year period; simulation averages were calculated for all HRUs, subject to the cropping rotation applicable to that particular HRU. Each environmental indicator was then multiplied by the number of hectares within each particular HRU to arrive at 'hectare-weighted' values by soil type. Finally, these 'hectare-weighted' values were aggregated for the whole basin and also sorted by cropping rotation for use in subsequent analyses. A similar 'hectare-weighting' analysis was performed for switchgrass only production by replacing the conventional commodity crops currently grown within the Delaware basin with switchgrass. Specifically, the SWAT model was used to obtain:

1. Annual yields for corn, soybeans, grain sorghum, and wheat for analysis in each of the four major cropping rotations in the basin;
2. Annual switchgrass yields as a function of N fertilizer level input (0 to 224 kg ha^{-1}); and
3. Annual reductions in sediment yield, surface runoff, NO_3– N in surface runoff, and edge-of-field erosion associated with producing switchgrass in place of the commodity crop rotations.

Before the environmental analysis could be conducted, it was first necessary to ensure that the SWAT model could reasonably predict crop yields in the Delaware basin within a tolerable error. Therefore, minor calibration of the SWAT plant growth module was performed by: (1) adjusting various SWAT plant growth input parameters; (2) running the SWAT model (with the new plant growth parameters) using a separate 4-year historical climate data set (1991–94); and (3) comparing predicted versus National Agricultural Statistics Service (NASS) average yields for all crops across the counties (Nemaha, Brown, Jackson, Atchison, and Jefferson) within the Delaware basin. This process was repeated several times until the change in the difference between historical and simulated yield had stabilized; the SWAT plant growth input parameters were then considered ‘optimal.’ Commodity crop yields (bushels ha^{-1}) for corn, soybeans, grain sorghum, and wheat were then simulated by the SWAT model (using the ‘optimal’ plant growth parameters) for each HRU over the 24-year period, subject to the tillage scenario applicable to that HRU (including N application levels). Simulated yields were filtered by the county where the crops were produced and averaged over the 24-year period. In general, the difference between historical and simulated yields was well within 10% across all crops. Annual switchgrass yields (Mg ha^{-1} y^{-1}) as a function of N fertilizer rates (0, 56, 112, 168, and 224 kg ha^{-1}) also were estimated using the SWAT model for all 552 HRUs over the 24-year analysis period. These values demonstrate the effect of applying various levels of N and helped determine reductions in sediment yield, surface runoff, NO_3–N in surface runoff, and edge-of-field erosion in the environmental and economic analyses. SWAT model predicted average yields ranged from 5.6 to 13.3 Mg ha^{-1} for 0–224 kg N ha^{-1}; simulated yield was 10.4 Mg ha^{-1} for 112 kg N ha^{-1} applied. The SWAT-predicted yield at 112 kg N ha^{-1} is comparable to switchgrass yields of 11.4 Mg ha^{-1} averaged across experimental plots with similar fertilizer inputs in the northern plains region (Walsh, 1994), and is also close to the range of yields (10.5–12.6 Mg ha^{-1}) from experimental switchgrass plots in Iowa and Nebraska with a fertilizer treatment of 120 kg N ha^{-1} applied (Vogel et al., 2002). The SWAT model was then used to establish a ‘baseline’ level of sediment, surface runoff, NO_3–N in surface runoff, and edge-of-field erosion for all 552 HRUs in the basin for each year of the 24-year period, based on the cropping rotations and field management practices outlined earlier. From this analysis, 24-year average annual values of the four environmental indicators were calculated. In addition, these variables were sorted by cropping rotation (corn–soybean, corn–soybean–wheat, grain sorghum–soybean, and grain sorghum–soybean–wheat). Table 1 presents general simulation results concerning the four environmental indicators across each of the four major cropping rotations and all three tillage practices considered.

The average decrease in sediment yield and edge-of-field erosion between the corn–soybean and corn–soybean–wheat rotations (Table 1) was expected due to the inclusion of wheat in the rotation; the same can be said of both grain sorghum–soybean rotations as well. Any decreases/increases in NO_3–N in surface runoff are a function of the rate of N utilization of each crop and soil type. While the increase in surface runoff between the corn–soybean rotation and corn–soybean–wheat versus grain sorghum–soybean rotation was somewhat unexpected (Table 1), it is entirely possible this could occur

Table 1
Sediment yield, surface runoff, NO_3–N in surface runoff, and edge-of-field erosion by cropping rotation

Cropping rotation	Sediment yield (Mg y^{-1})	Surface runoff (mm)	NO_3–N in surface runoff (kg)	Edge-of-field erosion (Mg y^{-1})
Corn–soybean				
Rotation total	176,915	5,652,102	82,874	788,612
Rotation average (ha^{-1})	2.61	83.4	1.2	11.6
Rotation area: 67,767 ha				
Corn–soybean–wheat				
Rotation total	3681	179,879	2132	11,704
Rotation average (ha^{-1})	2.26	110.4	1.3	7.2
Rotation area: 1630 ha				
Grain sorghum–soybean				
Rotation total	65,055	1,651,831	19,605	284,641
Rotation average (ha^{-1})	2.84	72.1	0.9	12.4
Rotation area: 22,908 ha				
Grain sorghum–soybean–wheat				
Rotation total	24,019	823,311	8146	85,415
Rotation average (ha^{-1})	2.09	29.1	0.7	7.4
Rotation area: 11,472 ha				
Total across rotations	269,670	8,307,123	112,757	1,170,372

Table 2
Comparison of reductions in sediment yield, surface runoff, NO_3–N in surface runoff, and edge-of-field erosion between the baseline cropping system and switchgrass at varying N application levels

Environmental indicator	Baseline cropping system	0 kg N ha^{-1} applied	56 kg N ha^{-1} applied	112 kg N ha^{-1} applied	168 kg N ha^{-1} applied	224 kg N ha^{-1} applied
Sediment yield						
Baseline cropping system (Mg y^{-1})	269,670					
Switchgrass (Mg y^{-1})		2500	1758	1633	1583	1569
% Reduction (%)		99.1	99.4	99.4	99.4	99.4
Surface runoff						
Baseline cropping system (mm)	8,307,123					
Switchgrass (mm)		3,806,535	3,809,332	3,811,620	3,814,260	3,815,864
% Reduction (%)		55.2	55.2	55.2	55.1	55.1
NO_3–N in surface runoff						
Baseline cropping system (kg)	112,757					
Switchgrass (kg)		40,097	60,723	75,478	87,340	96,923
% Reduction (%)		65.3	47.5	34.7	24.5	16.2
Edge-of-field erosion						
Baseline cropping system (Mg y^{-1})	1,170,372					
Switchgrass (Mg y^{-1})		21,731	15,330	15,330	13,380	13,282
% Reduction (%)		98.2	98.7	98.7	98.9	98.9

and be attributed to: (1) differences in soil types and climate variables between production areas, and (2) simulated crop yield output responses over the analysis period.

The same analysis was performed for switchgrass production at each fertilizer input level to determine the effect of applying differing amounts of N, not only on switchgrass yield, but with respect to reductions in each of the four environmental indicators. Table 2 presents baseline data for the entire sub-basin for all four commodity crop rotations and switchgrass production with actual values of sediment, surface runoff, NO_3–N in surface runoff, and edge-of-field erosion and the percent reduction in each environmental indicator at each switchgrass production level.

From the data contained in Table 2, switchgrass production provides significant reductions in all four environmental indicators, especially sediment and edge-of-field erosion (∼99%). The amount of surface runoff hardly changed with increasing N application levels while reductions in NO_3–N in surface runoff decreased in proportion with the amount of N applied compared to the baseline condition. Simulation results indicate the production of switchgrass on all agricultural croplands in the Delaware basin provides significant reductions in each of the four environmental indicators considered.

3.2. Economic analysis

Table 3 presents production, inflection, and interest costs for each of the four commodity crops. Separate cost estimates were derived for conventional tillage, conservation tillage, and no-till. Table 4 presents cost of production budgets associated with switchgrass for each N application level. As is evident from the table, fertilizer is a major cost in the production of switchgrass. Using Eq. (2) with simulated yields derived from the SWAT model, long-term prices, and the cost estimates in Table 3, average net returns to land and management were \$53.18, \$68.49, \$58.22, and \$81.78 per hectare for the corn–soybean, corn–soybean–wheat, grain sorghum, and grain sorghum–wheat rotations, respectively. The difference in the average net return by crop rotation and associated area can be attributed to farmer choice of crop production in the previous 1–3 y before planting, as well as the market price of each individual grain crop at the time of this analysis. As the price of one commodity crop subsides or is forecast to subside, it is very likely that the acreages of potentially more profitable crops will become apparent. One chief advantage in producing energy crops for alternative energy use is that the farmer/landowner will have a 'floor' set for production, versus having to incur the potential risk associated with commodity crop markets.

Table 5 presents break-even prices for switchgrass production versus the four commodity crop rotations as a function of N application. The lowest break-even price for each crop rotation corresponds with the highest N application. The break-even prices (\$ Mg^{-1}) for the highest N application rate for the corn–soybean and grain sorghum–soybean rotations are approximately \$1.70 lower than the break-even price for

Table 3
Production costs (\$ ha^{-1}) and inflection parameter equations for corn, soybeans, grain sorghum, and wheat for conventional, conservation, and no-till field management practices

Tillage system	Corn production costs (\$ ha^{-1})	Soybean production costs (\$ ha^{-1})	Grain sorghum production costs (\$ ha^{-1})	Wheat production costs (\$ ha^{-1})
Conventional tillage	\$368.97	\$280.35	\$307.39	\$207.26
Conservation tillage	\$356.08	\$258.73	\$295.93	\$198.42
No-till	\$349.33	\$232.85	\$299.83	\$207.70
Inflection/extra harvest cost	(Yield-202.5)*0.102	(Yield-83.9) * 0.126	(Yield-150.7)* 0.11	(Yield-56.8) * 0.124

Table 4
Switchgrass cost-of-production budget

	0 kg N ha^{-1} applied	56 kg N ha^{-1} applied	112 kg N ha^{-1} applied	168 kg N ha^{-1} applied	224 kg N ha^{-1} applied
Cost items (do not vary by yield, \$ ha^{-1})					
Seed	\$9.26	\$9.26	\$9.26	\$9.26	\$9.26
Fertilizer	\$0.00	\$19.76	\$39.52	\$59.28	\$79.04
Tandem disk	\$3.11	\$3.11	\$3.11	\$3.11	\$3.11
Tandem disk	\$3.11	\$3.11	\$3.11	\$3.11	\$3.11
Field cultivate	\$2.84	\$2.84	\$2.84	\$2.84	\$2.84
Plant	\$4.62	\$4.62	\$4.62	\$4.62	\$4.62
Fertilizer application	\$8.69	\$8.69	\$8.69	\$8.69	\$8.69
Swathing	\$20.90	\$20.90	\$20.90	\$20.90	\$20.90
Interest	\$2.62	\$3.61	\$4.59	\$5.58	\$6.57
Sub-total	\$55.18	\$75.93	\$96.68	\$117.42	\$138.17
Cost items (vary by yield, \$ Mg^{-1})					
Baling	\$10.58	\$10.58	\$10.58	\$10.58	\$10.58
Interest	\$0.53	\$0.53	\$0.53	\$0.53	\$0.53
Sub-total	\$11.11	\$11.11	\$11.11	\$11.11	\$11.11

the corn–soybean–wheat rotation and \$3.80 lower than the break-even price for the grain sorghum–soybean–wheat rotation.

It should be noted that the economic analysis results presented herein are applicable only to the rotations considered in this study and the areas (e.g. soil types) upon which they were produced. Furthermore, the order in which each commodity crop was produced (i.e. for a corn–soybean rotation, corn is produced in year 1, soybeans in year 2, etc.) has an effect upon the economic outcome. If the order were reversed between corn and soybeans, the net return per hectare could change due to differing yields. However, this analysis does provide a methodology by which to estimate and compare economics associated with both commodity crop production from varying rotations and switchgrass production to determine ‘general’ edge-of-field values to determine feasibilities associated with using switchgrass as an alternative energy source.

To employ switchgrass as an alternative energy source, the quantities of switchgrass that can be produced and at what particular price need to be determined. Supply curves for switchgrass in all 552 HRUs were generated. Supply curves refer to the quantity of switchgrass available for removal from the field at a set price which is a function of the break-even price of switchgrass (itself a function of the individual commodity crops that comprise each rotation’s net return per hectare) and the corresponding switchgrass yield. Switchgrass supply curves were developed for edge-of-field break-even prices (\$ Mg^{-1}) of \$0–\$10.99, \$11–\$38.49 in increments of \$5.49 Mg^{-1}, and \$38.50 and greater for all five switchgrass production scenarios (0–224 kg N ha^{-1} applied). Table 6 presents supply curve data and the corresponding total savings in sediment yield, surface runoff, NO_3–N in surface runoff, and edge-of-field erosion. In nearly every case concerning switchgrass production at the five N application levels, at least 50% of the environmental savings in each of the four indicators could be attained at a break-even price of \$22–\$27.49 Mg^{-1} or less (edge-of-field cost). In some instances, a much greater percentage of environmental savings could be attained using this price.

3.3. Percent reductions in reservoir sediment loading through selective switchgrass plantings

Additional analysis was performed to determine the number of hectares and the required cost associated with controlling certain percentages of sediment into Perry reservoir through the use of selective switchgrass planting (by HRU) within the Delaware basin. The 24-year average annual sediment yields for each of the 552 HRUs were sorted, in descending order, according to the percentage contributed by each HRU to the

Table 5
Break-even prices (\$ ha^{-1} and \$ Mg^{-1}) for switchgrass production in relation to corn–soybean, corn–soybean–wheat, grain sorghum–soybean, and grain sorghum–soybean–wheat rotations as a function of N application levels

Cropping rotation	Break-even	0 kg N ha^{-1} applied	56 kg N ha^{-1} applied	112 kg N ha^{-1} applied	168 kg N ha^{-1} applied	224 kg N ha^{-1} applied
Corn–soybean	\$ ha^{-1}	\$192.09	\$235.37	\$273.63	\$309.57	\$343.75
	\$ Mg^{-1}	\$36.04	\$28.77	\$26.54	\$25.45	\$24.99
Grain sorghum–soybean	\$ ha^{-1}	\$184.26	\$228.99	\$269.55	\$307.24	\$342.81
	\$ Mg^{-1}	\$33.22	\$27.21	\$25.63	\$25.01	\$24.94
Corn–soybean–wheat	\$ ha^{-1}	\$194.34	\$243.76	\$285.41	\$323.89	\$359.46
	\$ Mg^{-1}	\$35.34	\$29.18	\$27.49	\$26.74	\$26.61
Grain sorghum–soybean–wheat	\$ ha^{-1}	\$195.28	\$245.22	\$288.74	\$327.65	\$363.61
	\$ Mg^{-1}	\$41.05	\$32.33	\$29.71	\$28.86	\$28.78

Table 6
Switchgrass supply curves and total savings in sediment yield, surface runoff, NO_3–N in surface runoff, and edge-of-field erosion

Switchgrass (kg N ha^{-1} applied)	# of metric tons of switchgrass and cumulative sediment yield, surface runoff, NO_3–N in surface runoff, and edge-of-field erosion savings						
	\$0–\$10.99 Mg^{-1}	\$11.00–\$16.49 Mg^{-1}	\$16.50–\$21.99 Mg^{-1}	\$22.00–\$27.49 Mg^{-1}	\$27.50–\$32.99 Mg^{-1}	\$33.00–\$38.49 Mg^{-1}	\$38.50+ Mg^{-1}
0 kg N ha^{-1} applied	4,599	25,064	39,605	91,404	247,343	375,228	580,150
Sediment yield (Mg y^{-1})	153,236	686,747	1,473,597	4,122,366	11,384,525	18,623,614	34,254,480
Surface runoff (mm)	42	19,080	39,890	115,255	370,314	608,244	882,678
NO_3–N in surface runoff (kg)	167,344	819,247	1,263,013	2,165,096	4,415,112	6,325,147	8,499,945
Edge-of-field erosion (Mg y^{-1})	797	4445	7428	13,976	33,557	52,555	75,562
56 kg N ha^{-1} applied	2623	44,117	81,508	375,202	678,492	797,834	871,654
Sediment yield (Mg y^{-1})	13	21,201	42,743	156,363	240,788	260,001	272,541
Surface runoff (mm)	34,230	530,392	811,233	2,556,452	3,944,955	4,418,610	4,693,112
NO_3–N in surface runoff (kg)	58	3345	5075	23,675	45,056	52,874	54,935
Edge-of-field erosion (Mg y^{-1})	33	48,695	108,138	555,114	961,990	1,076,278	1,141,647
112 kg N ha^{-1} applied	72	44,073	129,724	664,036	963,421	1,041,606	1,084,655
Sediment yield (Mg y^{-1})	0.35	14,044	53,540	213,255	255,273	267,503	272,666
Surface runoff (mm)	814	454,557	947,993	3,356,443	4,324,507	4,561,411	4,690,824
NO_3–N in surface runoff (kg)	2.28	2010	3412	24,129	37,519	39,356	40,180
Edge-of-field erosion (Mg y^{-1})	0.75	35,573	158,318	821,369	1,053,280	1,116,823	1,142,908
168 kg N ha^{-1} applied	28,193	160,986	189,179	880,368	1,142,625	1,249,808	1,257,135
Sediment yield (Mg y^{-1})	5985	63,263	69,248	232,289	259,196	271,896	272,716
Surface runoff (mm)	273,911	909,281	1,183,192	3,720,931	4,392,631	4,668,190	4,688,185
NO_3–N in surface runoff (kg)	792	1408	2200	19,207	26,418	28,248	28,318
Edge-of-field erosion (Mg y^{-1})	14,275	189,073	203,348	919,134	1,073,548	1,138,532	1,143,497
224 kg N ha^{-1} applied	0	11,669	206,260	1,047,363	1,291,440	1,405,171	n/a
Sediment yield (Mg y^{-1})	0	54	68,968	236,182	260,785	272,730	n/a
Surface runoff (mm)	0	110,488	1,171,505	3,844,828	4,426,641	4,686,581	n/a
NO_3–N in surface runoff (kg)	0	79	1012	12,333	17,331	18,735	n/a
Edge-of-field erosion (Mg y^{-1})	0	108	205,744	952,362	1,081,004	1,143,695	n/a

Table 7
Replacement of baseline cropping system acreage with switchgrass to reduce sediment loading into Perry reservoir by 10, 25, and 40%

Cropping rotation	10% Reduction in sediment loading (ha)	Total cost to achieve 10% reduction ($)	25% reduction in sediment loading (ha)	Total cost to achieve 25% reduction ($)	40% Reduction in sediment loading (ha)	Total cost to achieve 40% reduction ($)
Corn–soybean	5040	$1,365,331	19,363	$5,245,051	35,185	$9,530,995
Corn–soybean–wheat	0	$0	0	$0	696	$195,822
Grain sorghum–soybean	2532	$675,165	5704	$1,520,686	9349	$2,492,219
Grain sorghum–soybean–wheat	743	$211,063	2089	$593,623	3863	$1,097,493
Total	8315	$2,251,559	27,156	$7,359,360	49,093	$13,316,529

total basin sediment yield. Cumulative sediment yield totals were calculated to determine the HRUs and corresponding number of hectares which resulted in reservoir sediment loading reductions of 10, 25, and 40%. These totals were further refined by sorting each of the three percentage categories by the cropping rotations produced on the hectares that comprise that particular category.

In addition, the total cost associated with achieving these three percentage reductions was determined using a cropping rotation-specific switchgrass break-even price ($ ha^{-1}). The additional revenue required to achieve 10, 25, and 40% sediment yield reductions was obtained by averaging the five switchgrass breakeven costs for each cropping rotation (given in Table 5) and multiplying these values by the number of hectares of each cropping rotation required for each target percentage reduction. Table 7 presents the total number of hectares for each of the four cropping rotations and the corresponding additional revenue required to achieve 10, 25, and 40% sediment yield reductions in the Delaware basin.

3.4. Switchgrass water quality payments

In order for switchgrass to potentially provide the water quality benefits determined in the previous analyses, it must be able to compete with both conventional commodity crop production and have a delivered price competitive as an alternative energy source. A switchgrass water quality payment is defined here as the amount of money, on a per hectare or per Mg basis of switchgrass produced, that the state of Kansas and/or the federal government would need to pay to

Table 8
Required water quality payments to achieve $5.68 GJ^{-1} delivered energy costs

Cropping rotation		0 kg N ha^{-1} applied	56 kg N ha^{-1} applied	112 kg N ha^{-1} applied	168 kg N ha^{-1} applied	224 kg N ha^{-1} applied
Corn–soybean	Edge-of-field ($ GJ^{-1})	$1.96	$1.56	$1.43	$1.37	$1.34
	Deliverable energy cost ($ GJ^{-1}), Pelleting	$6.90	$6.50	$6.39	$6.32	$6.30
	Water quality payment ($ Mg^{-1}) to reach $5.68 GJ^{-1}	$22.17	$14.89	$12.67	$11.58	$11.12
	Water quality payment ($ ha^{-1}) to reach $5.68 GJ^{-1}	$118.16	$121.87	$130.61	$140.89	$152.97
Grain sorghum–soybean	Edge-of-field ($ GJ^{-1})	$1.81	$1.47	$1.38	$1.34	$1.34
	Deliverable energy cost ($ GJ^{-1}), Pelleting	$6.75	$6.41	$6.33	$6.30	$6.29
	Water quality payment ($ Mg^{-1}) to reach $5.68 GJ^{-1}	$19.35	$13.34	$11.76	$11.14	$11.07
	Water quality payment ($ ha^{-1}) to reach $5.68 GJ^{-1}	$107.30	$112.26	$123.65	$136.91	$152.13
Corn–soybean–wheat	Edge-of-field ($ GJ^{-1})	$1.94	$1.58	$1.49	$1.44	$1.44
	Deliverable energy cost ($ GJ^{-1}), Pelleting	$6.86	$6.53	$6.43	$6.39	$6.38
	Water quality payment ($ Mg^{-1}) to reach $5.68 GJ^{-1}	$21.47	$15.31	$13.62	$12.87	$12.74
	Water quality payment ($ ha^{-1}) to reach $5.68 GJ^{-1}	$118.07	$127.90	$141.38	$155.86	$172.11
Grain sorghum–soybean–wheat	Edge-of-field ($ GJ^{-1})	$2.26	$1.76	$1.61	$1.56	$1.56
	Deliverable energy cost ($ GJ^{-1}), Pelleting	$7.17	$6.70	$6.56	$6.51	$6.50
	Water quality payment ($ Mg^{-1}) to reach $5.68 GJ^{-1}	$27.18	$18.46	$15.84	$14.99	$14.91
	Water quality payment ($ ha^{-1}) to reach $5.68 GJ^{-1}	$129.30	$140.00	$153.93	$170.18	$188.36

the farmer/landowner for switchgrass to achieve a ‘target’ market price. In this study, the only alternative energy use scenario was for the switchgrass to be pelleted and used as a replacement for propane in space and water heating applications in homes and business within the Delaware basin.

The switchgrass production break-even price per hectare for each of the five N application levels for all four cropping rotations was converted into an analogous payment per Mg by dividing by the average annual switchgrass yields attainable over the areas upon which each cropping rotation was produced. These payments ($\$ \mathrm{Mg}^{-1}$ of switchgrass produced) were then converted to an edge-of-field energy payment ($\$ \mathrm{GJ}^{-1}$) by dividing them by a switchgrass energy conversion factor of $18.4 \mathrm{GJ\,Mg}^{-1}$. In the case of employing switchgrass as an alternative energy source, all costs associated with converting it into a useable energy source (e.g. transportation, loading, processing, and conversion) must be considered when making a valid comparison to the competing alternative fossil-based fuel source. An analysis was conducted to determine the final deliverable price associated with transporting switchgrass to the pelleting mill, processing the switchgrass into useable pellets, management of the mill, and delivery to the end-use markets (King, 1999). From this analysis, a cost of $\$90.81 \mathrm{Mg}^{-1}$ was allocated to these expenses in addition to the in-field production cost calculated above. This is the delivered cost to the end consumer minus any mark-up for profit.

If this cost is less than the current and/or forecasted propane cost, then theoretically no water quality payment would be required and the farmer/landowner could produce switchgrass at a cost/price indifferent to that of a particular cropping rotation and the state and/or federal government would reap the water quality benefits associated with switchgrass production at no cost. If however, the projected/forecasted cost for energy were below the deliverable switchgrass energy cost, then the state and/or federal government would need to provide a supplemental or assistance payment that would ‘buy down’ the energy cost from switchgrass production to an amount equal to the expected propane cost.

Table 8 lists the deliverable energy costs ($\$ \mathrm{GJ}^{-1}$) associated with pelleting switchgrass for each of the commodity cropping rotations and N application levels considered. In addition, an analysis was run to determine the additional cost per Mg and hectare to achieve a delivered static propane energy cost of $\$5.68 \mathrm{GJ}^{-1}$ from pelletized switchgrass. This propane energy cost was chosen because it reflected the latest historical energy price trend for that particular area of Kansas. These payments ranged from a low of $\$11.07 \mathrm{Mg}^{-1}$ to a high of $\$27.18 \mathrm{Mg}^{-1}$ depending upon switchgrass yield level.

4. Summary and conclusions

This analysis indicates that switchgrass production on conventional agricultural cropland in northeast Kansas has distinct environmental advantages versus the traditional cropping rotations of corn–soybean, corn–soybean–wheat, grain sorghum–soybean, and grain sorghum–soybean–wheat. SWAT model simulations showed that sediment yield, surface runoff, NO_3–N in surface runoff, and edge-of-field erosion were reduced by an average of 99, 55, 34, and 98%, respectively, over the range (0–224 $\mathrm{kg\,N\,ha}^{-1}$) of N application levels.

Average net returns were $53.18, $68.49, $58.22, and $\$81.78 \mathrm{ha}^{-1}$ for the rotations of corn–soybean, corn–soybean–wheat, grain sorghum, and grain sorghum–wheat, respectively. These returns translated into break-even prices for switchgrass production ranging from $184.26 to $\$363.61 \mathrm{ha}^{-1}$ depending upon N application level and type of cropping rotation.

In nearly every scenario concerning switchgrass production, at least 50% of the environmental savings in sediment yield, surface runoff, NO_3–N in surface runoff, and edge-of-field erosion could be attained at an edge-of-field switchgrass price of $22–$\$27.49 \mathrm{Mg}^{-1}$ or less. In some instances, a much greater percentage of environmental savings could be attained within this price range. The conversion to switchgrass from any conventional commodity crop production scenario requires that farmers be fairly confident in the price they will receive for the crops (commodity or alternative energy), which in turn dictates the expense of converting to energy crop production. Hence, the real conversion expense is fairly variable with an inherent element of risk. In general, only farmers that believe they can sustainably produce energy crops at fairly higher yields, coupled with a potential demand for their crops through a long-term contract with a utility or energy service provider, would substantially reduce their expense.

The total deliverable energy cost associated with manufacturing switchgrass pellets and using them as a propane substitute was calculated using break-even prices for all four cropping rotations and a consideration of transportation, processing, and conversion costs. Deliverable energy costs ranged from a low of $\$6.29 \mathrm{GJ}^{-1}$ to a high of $\$7.17 \mathrm{GJ}^{-1}$. The magnitude of switchgrass water quality payments needed to achieve delivered energy costs of $\$5.68 \mathrm{GJ}^{-1}$ were determined and ranged from a low of $\$11.07 \mathrm{Mg}^{-1}$ to a high of $\$27.18 \mathrm{Mg}^{-1}$ depending upon switchgrass yield level.

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